

1. PI: K. N. Liou; Co-PI: Steve S.C. Ou

2. Title of Research Grant: Radiation Parameterization for Three-Dimensional Inhomogeneous Cirrus Clouds Applied to ARM Data and Climate Models

3. Scientific Goal(s):

Our project is concerned with the characterization of three-dimensional (3D) cirrus cloud fields using satellite and ground-based radar and lidar data available from the ARM Program and further development of the radiation parameterization for 3D inhomogeneous clouds with a specific emphasis on cirrus. Application of the proposed radiation parameterization to 3D cloud configurations generated by current GCMs and other relevant models will be carried out. We plan to construct 3D ice water content (IWC) and ice crystal mean effective size fields of cirrus clouds from a combination of data obtained from AVHRR (MODIS) channels and the vertical pointing mm radar. Lidar data and in-situ ice crystal size distributions measured from aircraft will be employed for validation of the retrieval results as well as the required parameterization. Moreover, we plan to refine and improve the radiation model developed for 3D inhomogeneous clouds for flux and heating rate calculations covering the entire solar and thermal IR spectra by comparing with established Monte Carlo results for solar radiative transfer. Finally, we plan to investigate differences between the results computed from pixel-by-pixel plane-parallel and 3D inhomogeneous models in terms of the domain-averaged fluxes and heating rates over typical GCM and meso-scale grids for a variety of cloud configurations. Ultimately, we wish to develop a computationally acceptable 3D radiation parameterization for cirrus clouds generated from a physically-based scheme developed for climate models.

4. Accomplishments

- Development of a 3D inhomogeneous radiative transfer model for clouds, with a particular focus on cirrus.
- Initiation of a novel technique for the mapping of 3D cirrus cloud fields based on a unification of satellite and mm-wave cloud radar data.

5. Progress Description

First, we have developed a 3D radiative transfer model to compute the transfer of solar and thermal infrared radiation in inhomogeneous cirrus clouds. The model utilizes a diffusion approximation approach (four-term expansion on the intensity) for application to inhomogeneous media employing Cartesian coordinates, and using the delta-function adjustment following the similarity principle to enhance computational accuracy. The extinction coefficient, single-scattering albedo, and asymmetry factor are functions of spatial position and wavelength and are parameterized in terms of the IWC and mean effective ice crystal size. We employ the correlated k-distribution method for incorporation of gaseous absorption in multiple scattering atmospheres. The general second-order partial differential radiative transfer equations with appropriate boundary conditions imposed are solved numerically by using an efficient successive over-relaxation method. For calculations of the broadband solar and thermal infrared (IR) fluxes

in inhomogeneous cirrus cloud layers, a total of 121 wavelengths are used to cover the solar (0.2-5 μm) and thermal infrared (5-50 μm) spectra. Comparisons of the model results with those from plane-parallel (PP) and Monte Carlo models show reasonable agreement for both broadband and monochromatic results. The PP method is shown to be a good approximation under the homogeneous condition when the cloud horizontal dimension is much larger than the cloud thickness. As the horizontal dimension decreases, clouds produce less infrared warming at the bottom as well as less cooling at the top, while more solar heating is generated within the cloud. For inhomogeneous cases, upwelling and downwelling fluxes display patterns corresponding to the extinction coefficient field. Cloud inhomogeneity also plays an important role in determining both solar and IR heating rate distributions. The present radiation parameterization is applied to potential cloud configurations generated from GCMs to investigate broken clouds and cloud overlapping effects on the domain-averaged heating rates. Clouds with maximum overlap tend to produce less heating than those with random overlap. Broken clouds show more solar heating as well as more IR cooling as compared to a continuous cloud field.

Second, we have innovated a remote sensing technology involving the construction of a three-dimensional field of the IWC and ice crystal mean size of cirrus clouds in space and time based on a combination of satellite and ground-based mm-wave cloud profiling radar observations. Recent advances in satellite remote sensing of cirrus clouds have demonstrated that their optical depth and mean effective ice crystal size can be retrieved from the operational NOAA AVHRR channels and the MODIS channels on board the NASA EOS/TERRA satellite launched in December 1999. Using SUCCESS and CEPAX MAS (MODIS Airborne Simulator) data, Rolland and Liou (2000) have shown that cirrus optical depth and mean effective ice crystal size can be determined from correlations of 0.63/1.6 and 0.63/2.13 μm wavelengths. Neither the 1.6 μm nor the 2.13 μm channel is available on the operational satellites at present. Our recent work in this area (Ou et al. 1999) shows that the correlation approach can be applied to the AVHRR 0.63 μm and 3.7 μm (total radiance) channels to infer cirrus cloud optical depth and mean effective ice crystal size. Mace et al. (1998) and Mace (2000, personal communication) have developed a technique for the retrieval of the IWC and ice crystal size of cirrus clouds by employing a combination of reflectivity and Doppler velocity and spectral width of the 94 GHz Doppler radar. In this approach, the ice crystal size distribution is assumed to conform to a modified gamma distribution consisting of hexagonal columns from which the Rayleigh-Gans theory is used to model the backscatter and estimate the fall velocity. A look-up table is constructed based on which retrievals of the cloud parameters can be carried out from radar backscatter data.

By a unification of the satellite retrieved optical depth and ice crystal size in the horizontal plane and the vertical profiles of IWC and ice crystal size derived from the cloud profiling radar, and on the basis of fundamental radiative transfer parameterization principle, a 3D cloud field can be constructed. In collaboration with Jay Mace and Ken Sassen, we have selected collocated and coincident AVHRR/NOAA and DOE/ARM mmCR data gathered at the CART site in the northern Oklahoma areas involving single cirrus and cirrus over low stratus during three ARM IOPs in the Spring of 1997 to test our methodology. Retrieval and analysis have been carried out to construct 3D IWC and DE fields. An example is illustrated in Fig. 1. Verification with collocated in-situ measurements of the ice crystal size distribution and IWC independently

derived from optical probes on board the University of North Dakota Citation will be an ongoing project. The MODIS data from TERRA/EOS will also be used for this study when it becomes available.

6. Fig. 1. Three-dimensional ice water content (IWC, g/m^3) and mean effective ice crystal size (DE, μm) determined from a unification of the optical depth and DE retrieval from the 0.63 and 3.7 μm AVHRR channels aboard the NOAA-14 satellite and the IWC and DE retrieved from the 94 GHz cloud radar (data provided by Jay Mace) over the ARM-SGP CART site at 2023 UTC on April 18, 1997. The 3D IWC and DE results are presented in xy, yz, and xz planes over a 40 km x 40 km x 4.5 km domain. Validation of the retrieval results based on independent in-situ measurements is essential to establish relative uncertainties (K. N. Liou, UCLA, July 2000/DOE/ARM).

7. Refereed Publications:

Gu, Y. and K. N. Liou, 2000: Radiation parameterization for three-dimensional inhomogeneous cirrus clouds: Application to climate studies. *J. Climate*, (in revision).

8. None

9. None

3D Cloud Mapping in a Mesoscale Grid

